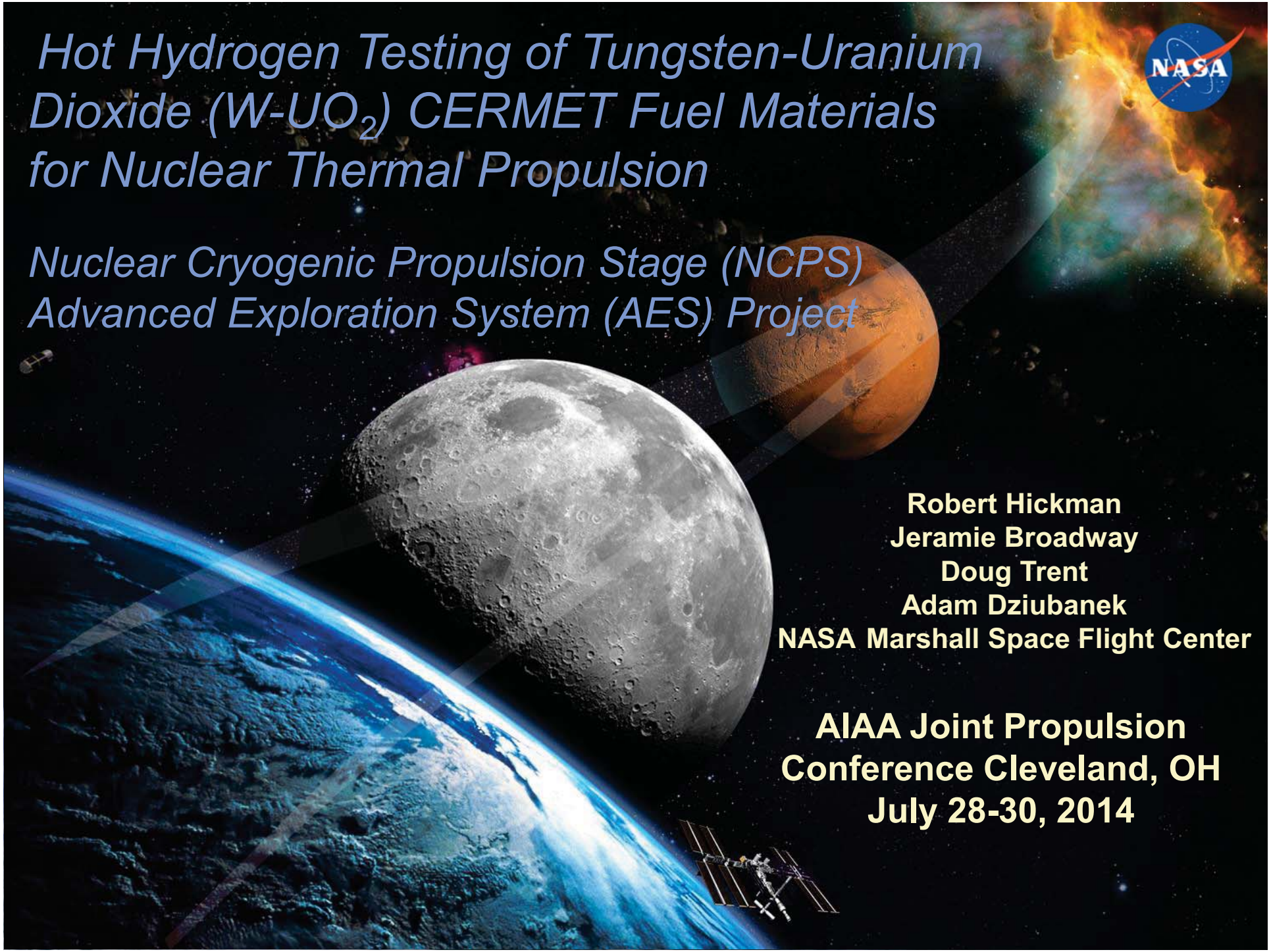
Hot Hydrogen Testing of Tungsten-Uranium Dioxide (W-UO_2) CERMET Fuel Materials for Nuclear Thermal Propulsion

Nuclear Cryogenic Propulsion Stage (NCPS)
Advanced Exploration System (AES) Project



Robert Hickman
Jeramie Broadway
Doug Trent
Adam Dziubanek
NASA Marshall Space Flight Center

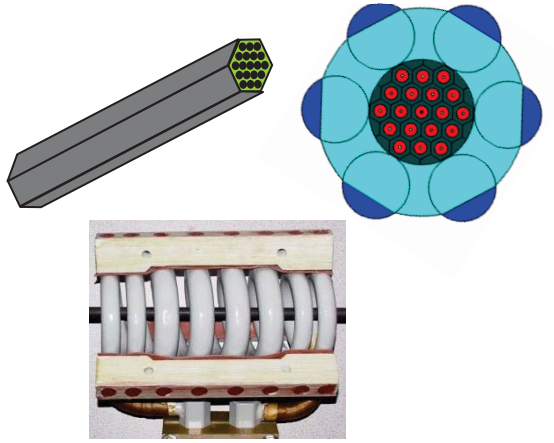
AIAA Joint Propulsion Conference Cleveland, OH
July 28-30, 2014

Outline

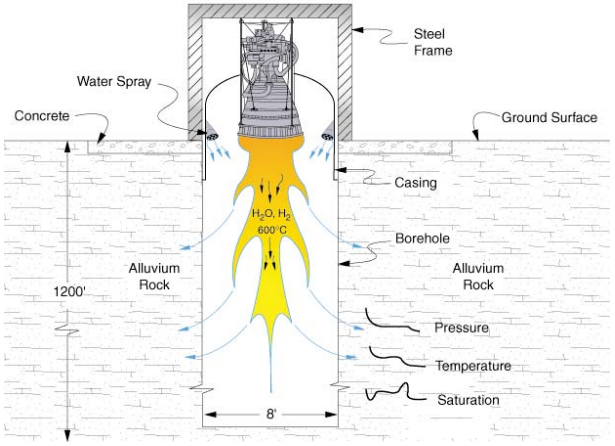
- NCPS Overview
- Heritage CERMET Development
- Non-Nuclear Fuels Testing
- Compact Fuel Element Environmental Test (CFEET)
 - System development
 - Current configuration and validation
- Hot Hydrogen Testing of W-UO2
- Non-Uniform RF Heating Profile
- Forward Plan and Summary

Nuclear Cryogenic Propulsion Stage (NCPS)

- NCPS started in FY2012 to assess affordability and viability of NTP
- NTP is game changing for space exploration
 - High ISP, reduced trip times
- Overall tasks
 - Conceptual design and architecture integration
 - **Fuel Fabrication and Test**
 - Nuclear Thermal Rocket Element Environmental Simulator (NTREES)
 - Affordable Development /Qualification Strategy
- Critical need for fuels development
 - Lack of qualified fuel material is a key risk
 - Development of stable fuel form is a critical path, long lead activity
- Enables fuel optimization and ground test



Fuel Element Design, Fabrication, and Test



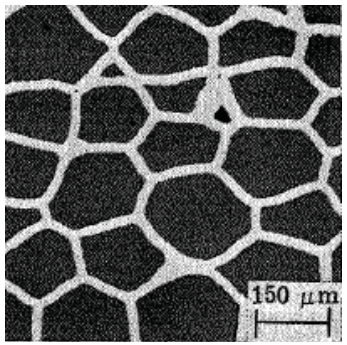
Engine Ground Test

Heritage CERMET Fuel Development

- CERMET fuels consist of a metal matrix with embedded ceramic fuel particles
 - W matrix (high melting point, H2 compatibility)
 - UO_2, UN, (U,Zr)CN fuel particles
- Current work is based on GE710, ANL, and NASA LeRC development Programs
 - Must recapture capabilities and processes
- Data is not sufficient to support selection of a baseline fabrication technique
 - Large variation in materials, processes, and testing
- Significant progress made to characterize fuel
 - Fuel loss and failure mechanisms are known
 - Materials and process options to improve fuel performance are known



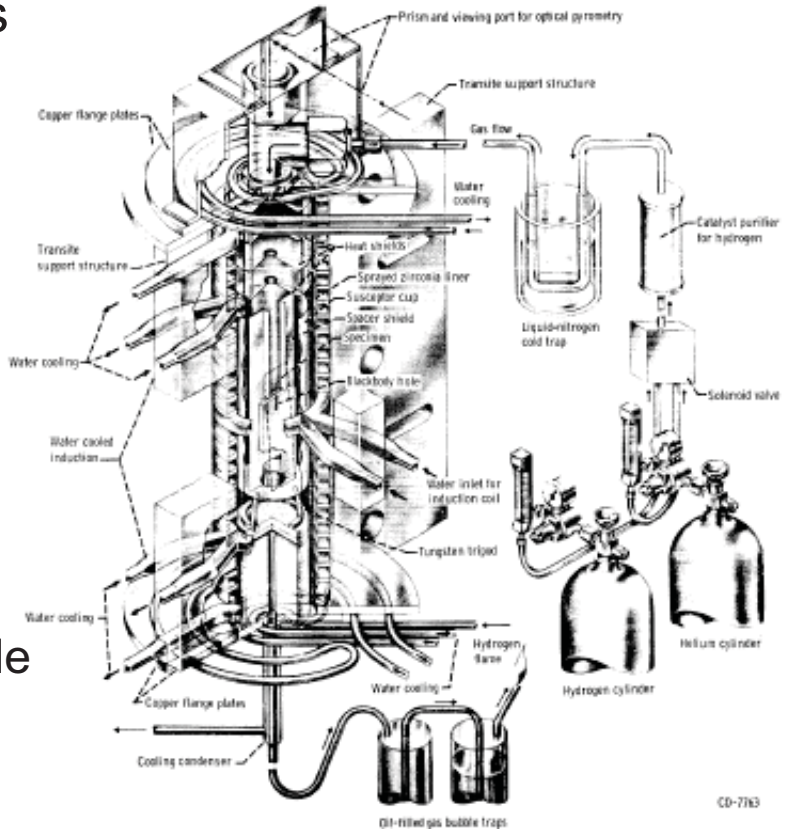
W-UO2 CERMET Samples fabricated during ANL Program



W - light phase, UO2 - dark phase

Non-Nuclear Hot H2 Screening and Evaluation

- Need affordable approach to evaluate fuels
 - Fuel loss and stability
 - Validate M&P and designs
 - Perform prior to expensive nuclear testing
- Hydrogen testing used extensively on previous programs
- NASA-LeRC induction furnace
 - 2760 C specimen temperatures
- ANL H_2 test loops (small & large)
 - Resistively heated H2 flowing through sample
 - Up to 2450 C
- Rover/NERVA test facilities
 - Full Length H_2 test systems at LANL & WANL
 - Resistively heated (1MW) elements

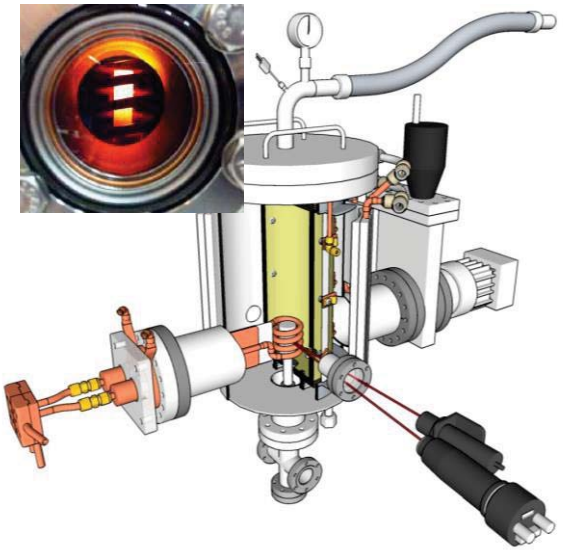


NASA-LeRC Induction Furnace

Previous capabilities no longer exist and very limited info on systems

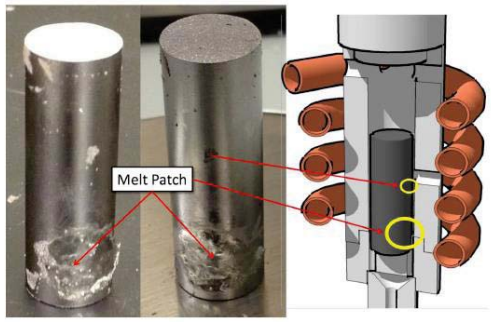
Compact Fuel Element Environment Test (CFEET)

- Affordable, rapid screening of subscale samples
- Utilizes RF induction heating
- Numerous system modifications
 - Power supply, cooling water, RF coil, data acquisition, H2 feed, and sample support
- Initial testing with 15kW RF power supply
 - Operational tests using W and W-Re-HfN CERMET
 - 2565 C in vacuum, 2042 C in flowing H2
 - Temps limited by power supply
- System re-design and upgrade to 50 kW

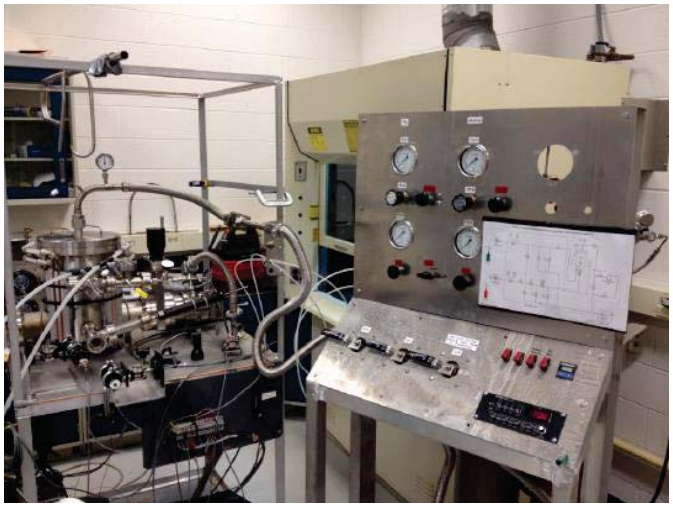




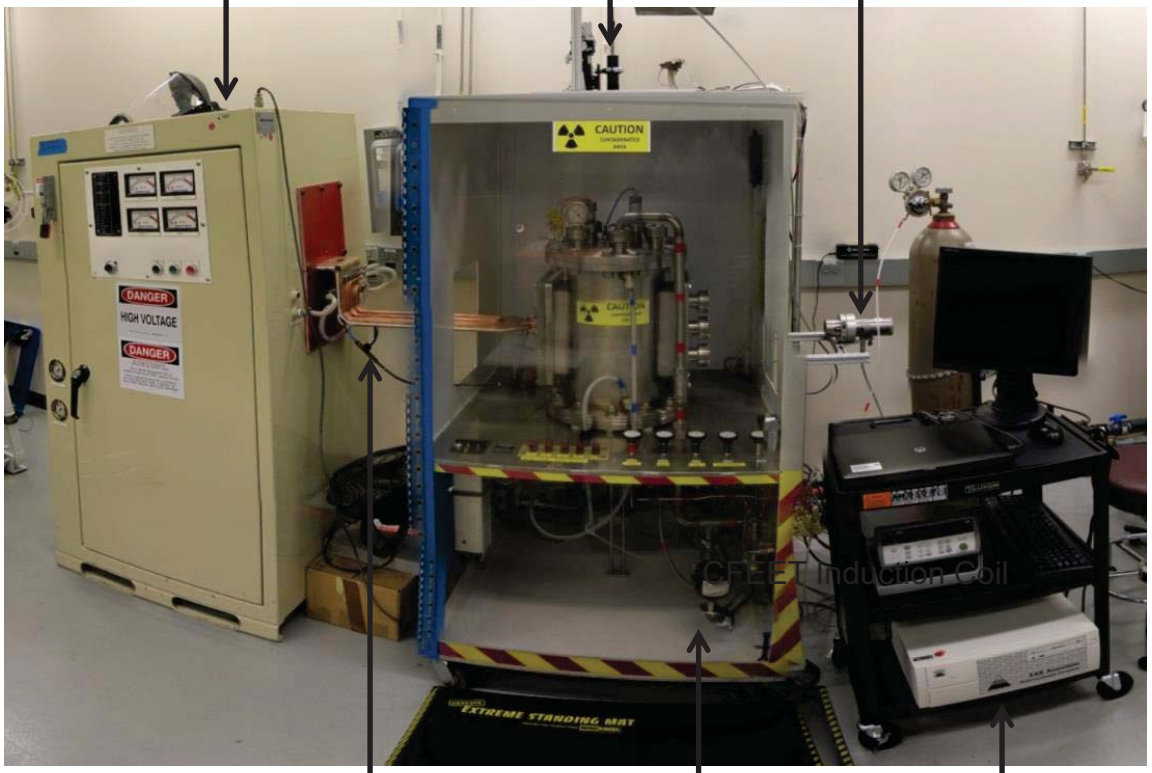
Pre/Post test W-Re-HfN CERMET samples



Pure W samples



Current CFEET Configuration



- Fully operational with DU
- 16.5 SLPM H_2 Flow Rate
- >2500 C, 2 hour run times

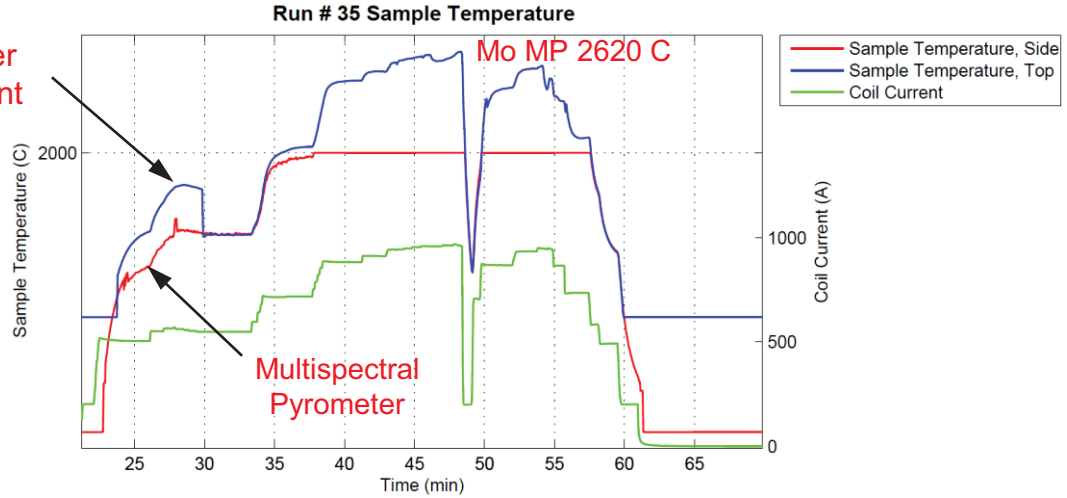


CFEET Chamber and RF Induction Coil

CFEET Temperature Validation

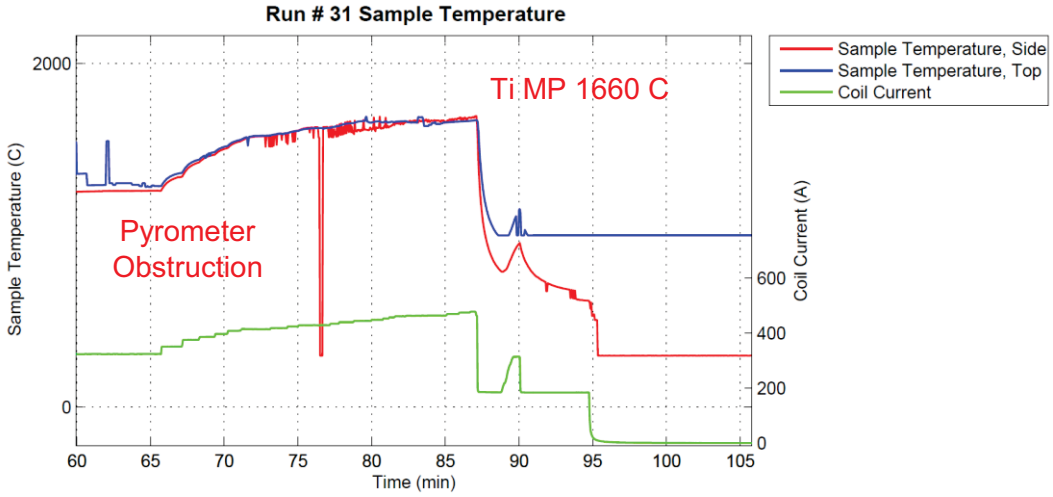
- Multispectral pyrometer up to 2000 C, 2 color up to 3000 C
 - 2 color pyrometer adjustment to multispectral at 1500 C

2 Color Pyrometer Adjustment





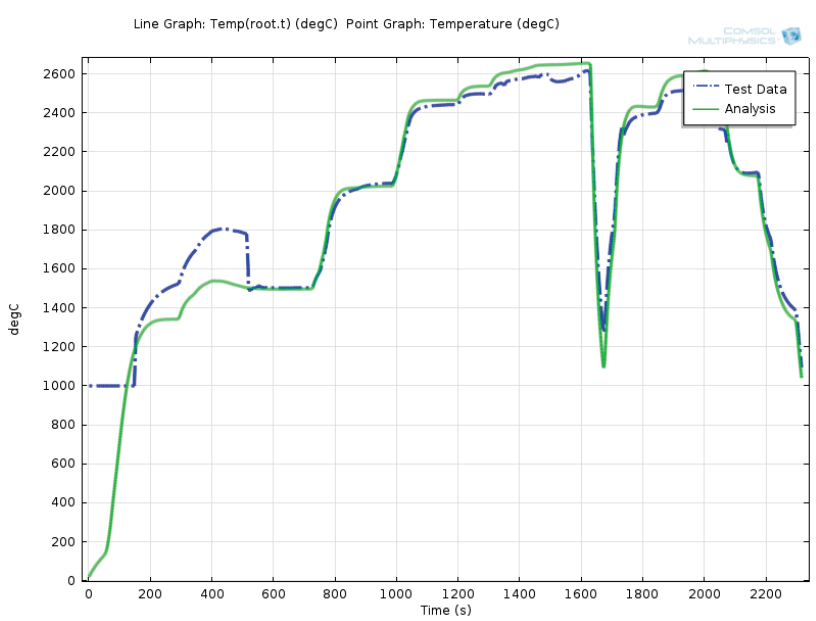
Molybdenum Sample Post Test (1” length)



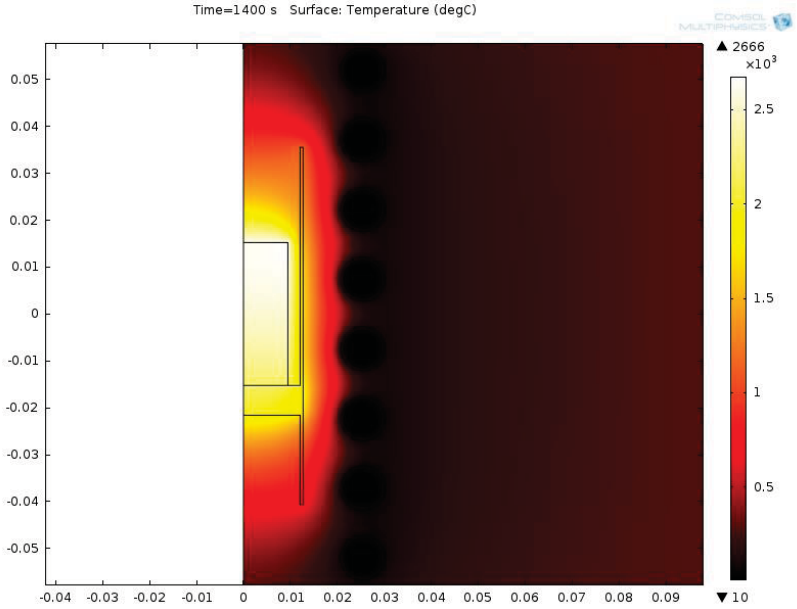


Titanium Sample Post Test (1” length)

CFEET Model Validation



Molybdenum melt test calibration cycle and model temperature data



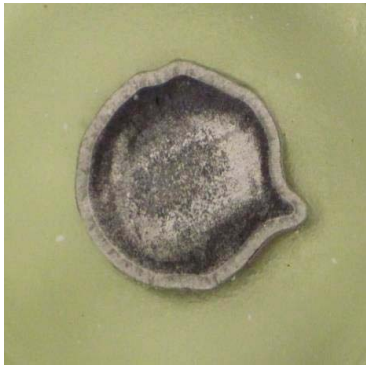
Multiphysics model showing surface temperature for a Mo sample in CFEET

- Multiphysics model uses CFEET RF current data to estimate magnetic flux density and sample temperatures
 - Includes fully coupled flowing H2 and material properties

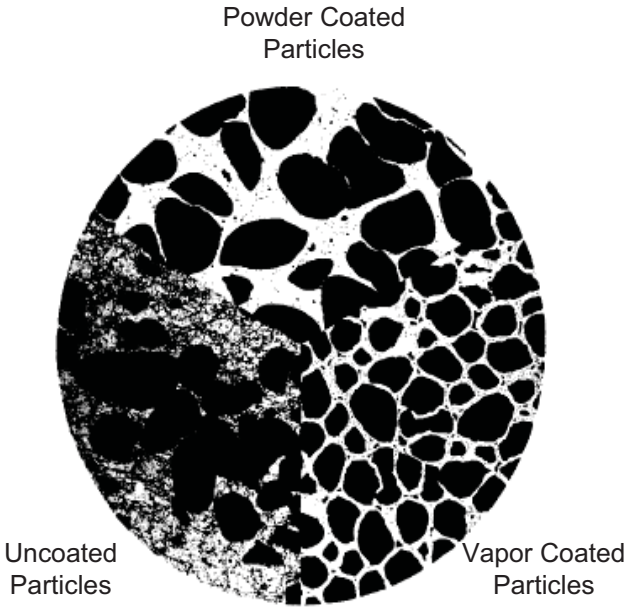
W-UO_2 Sample Testing in CFEET

- Initial W-UO2 samples are not optimized
 - UO_2 agglomeration
 - No interconnected W matrix
 - Low density (interconnected porosity)
 - No protective W claddings
 - No UO_2 stabilizers
- Testing mainly to understand CFEET system
 - RF coupling and temperature control
- Evaluate UO_2 vaporization

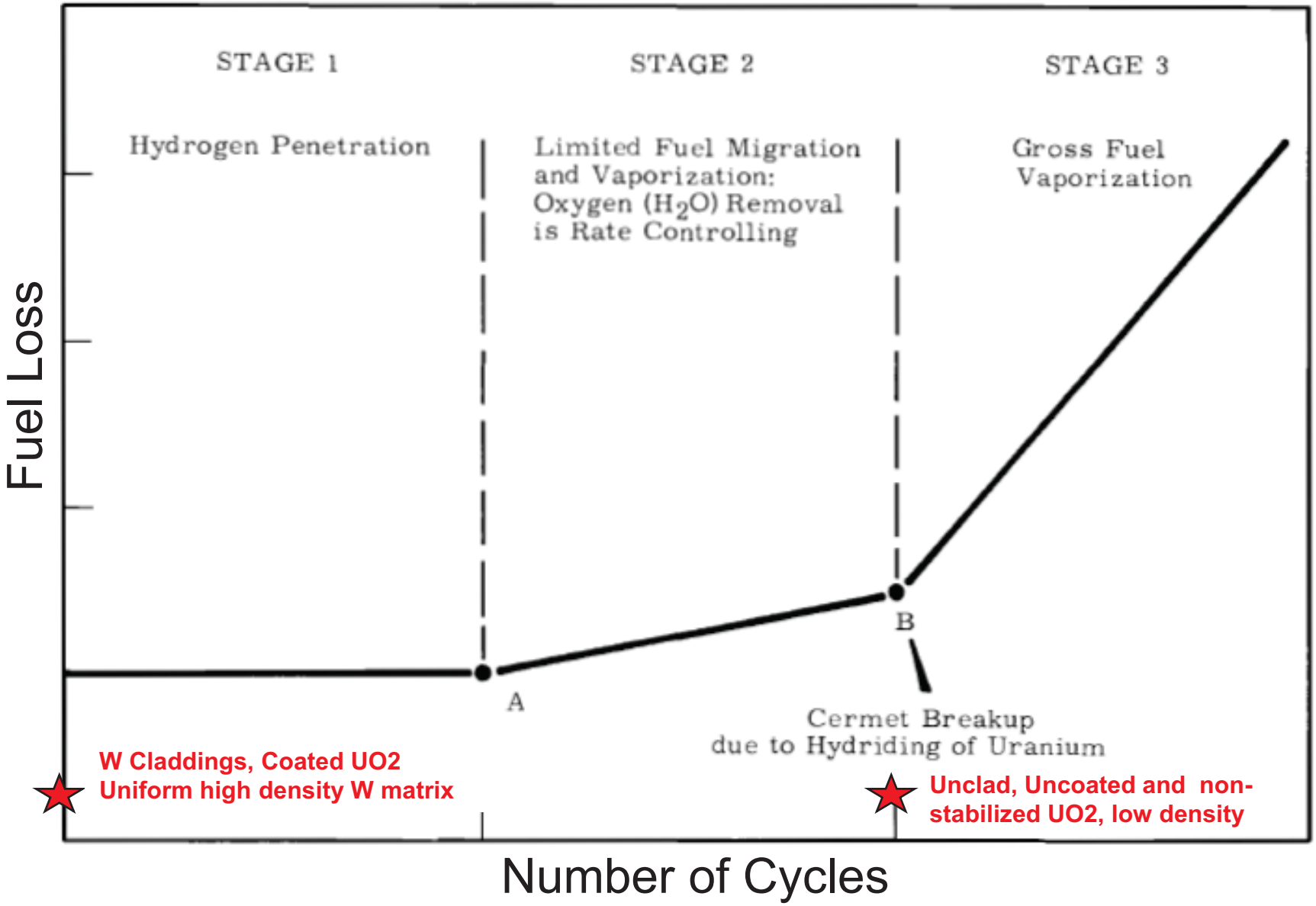
- Samples can only get better with further materials and process development!



UO2 agglomeration in current samples. Dark regions are UO2, light regions are W.

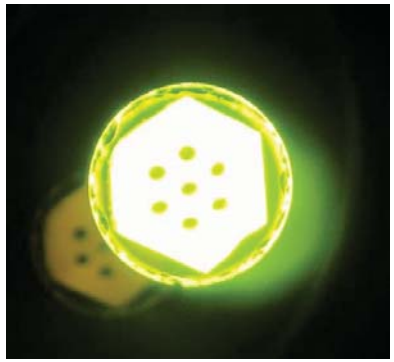


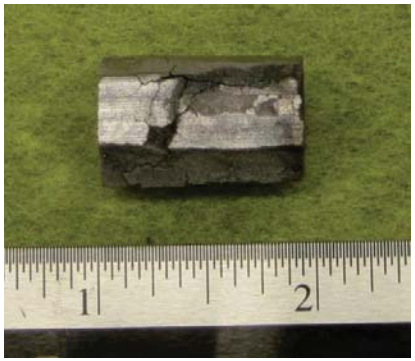
Stages of W-UO_2 Decomposition



Initial W-UO_2 Sample Testing in CFEET

- 7-Hole W-UO_2 sample cycled for 30 minutes at 1650 C in flowing H_2 to remove surface oxides and contamination
 - 10% of 50 KW power supply, No visible change in sample
- 2nd cycle of 7-hole sample with slow ramping up to 2500 C
 - Cycle terminated after 30 sec at ~2400 C due to rapid UO_2 vaporization (pyrometer sight glass completely covered with U deposits)
 - Cracking, particle deposition on the hot end and 1.5% weight loss
- W-UO_2 slug sample cycled for 10 minutes at 2500 C
 - Sample reduced to powder after cooling

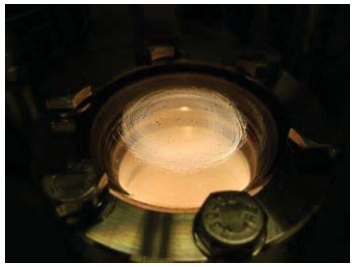




7-hole W-UO_2 in CFEET and post testing up to 2400 C

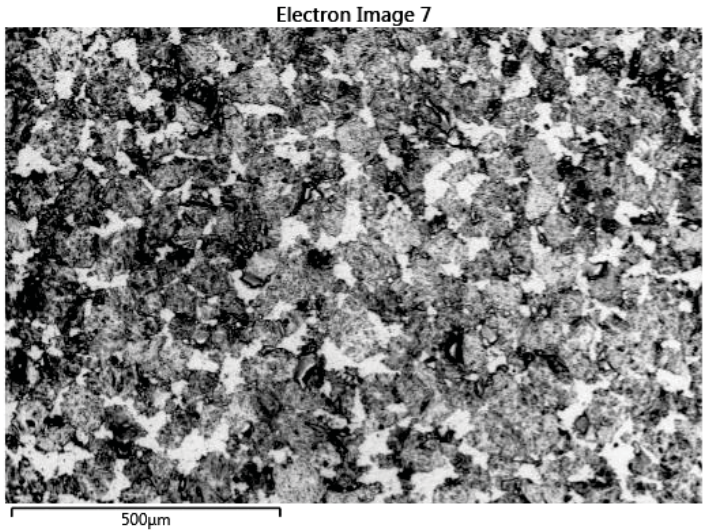


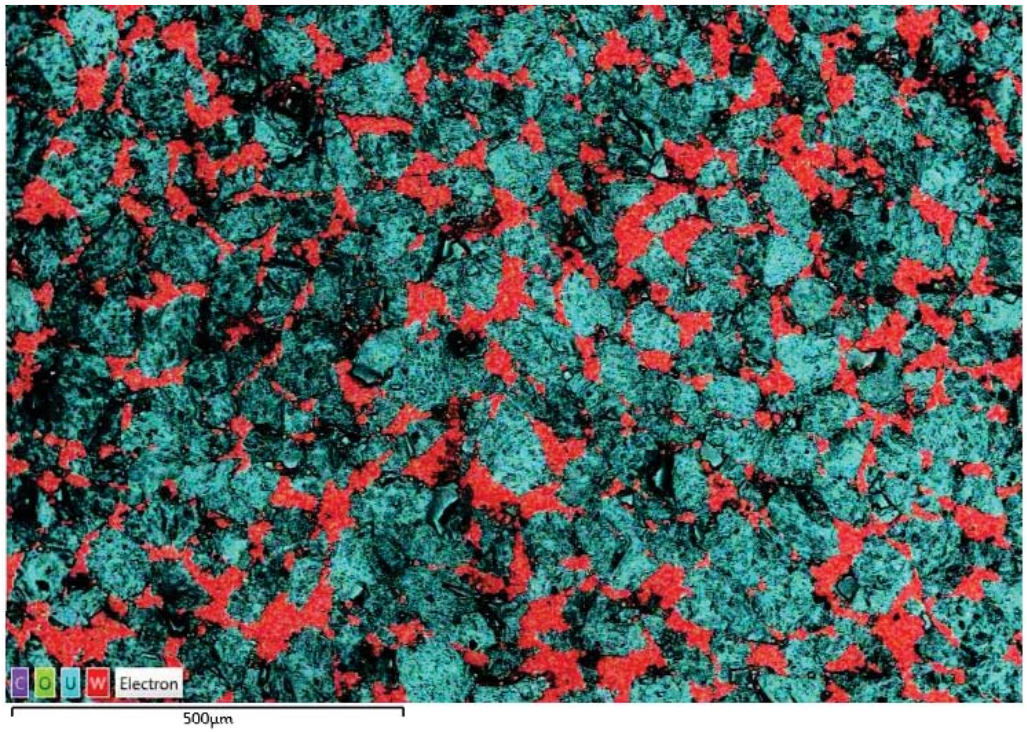
W-UO2 slug after 10 min in CFEET at 2500C

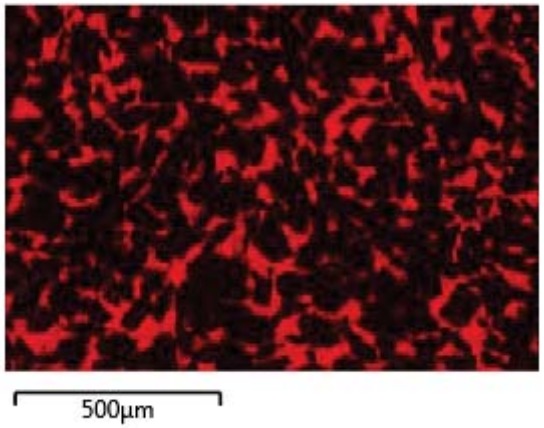


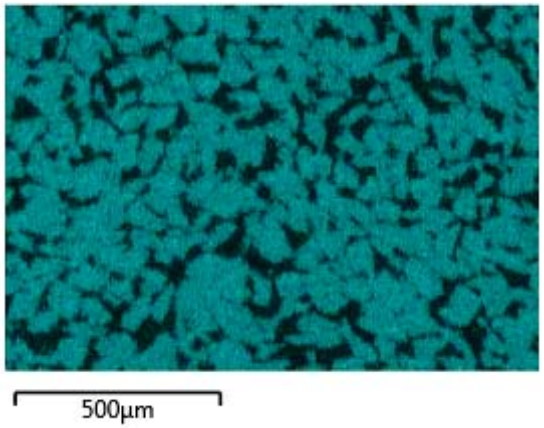
Build up on CFEET Sight Glass

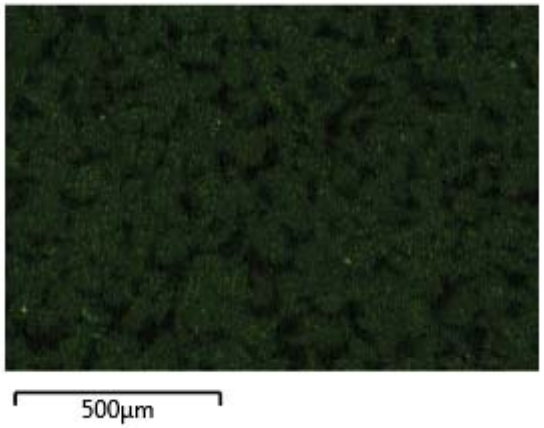
W-UO_2 Phase Map Pre CFEET Test



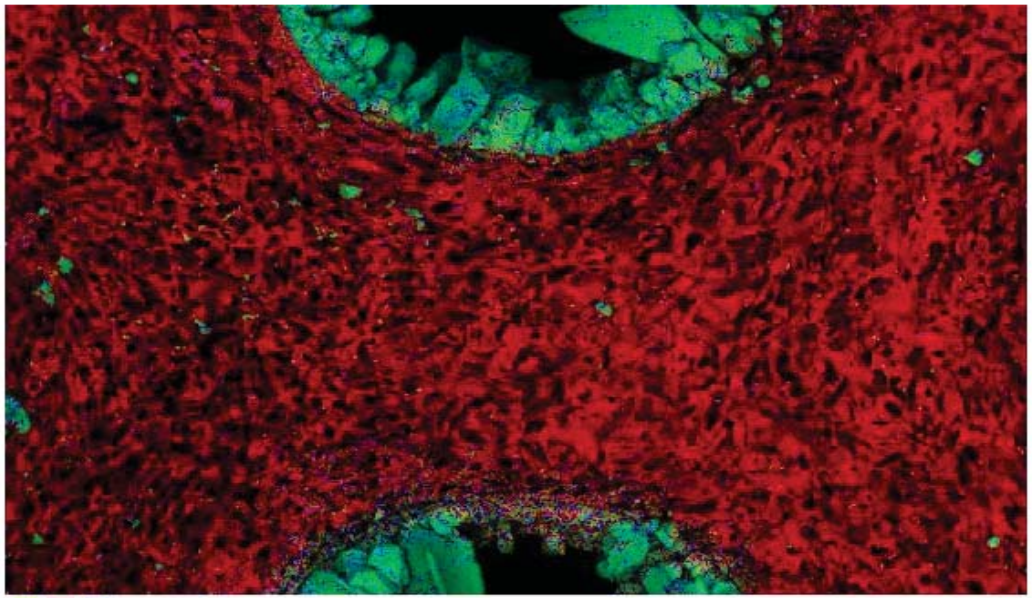




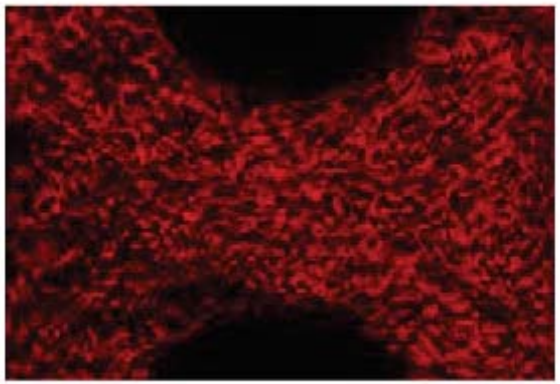




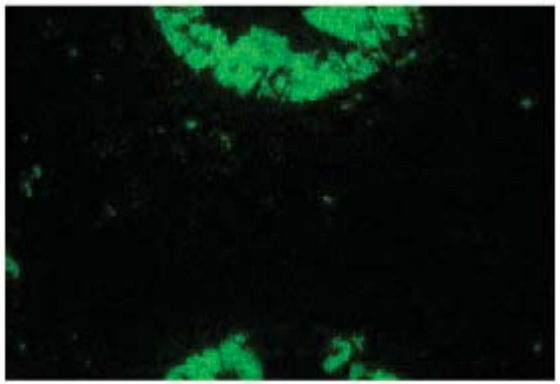
W-UO_2 Phase Map Post CFEET Testing



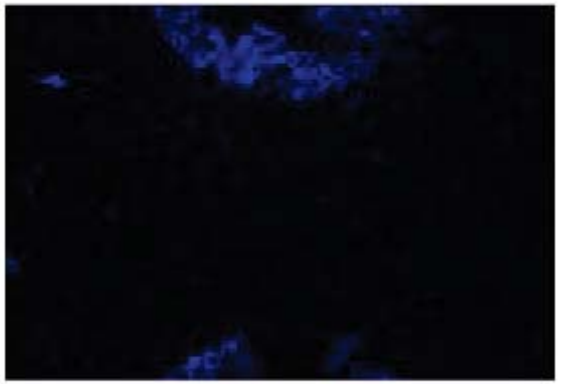
W M series



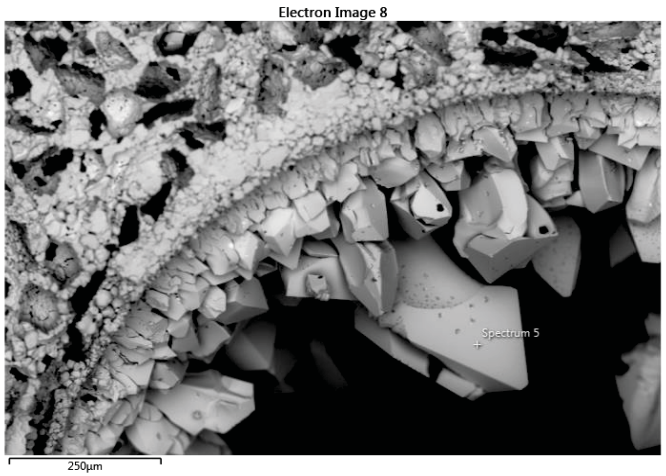
U M series

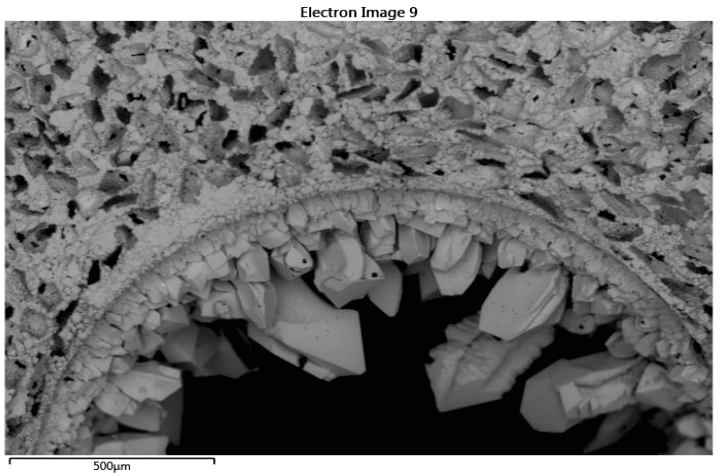


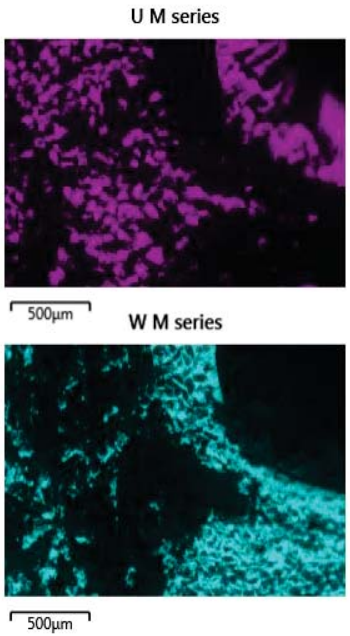
O K series



WUO_2 Post CFEET Test







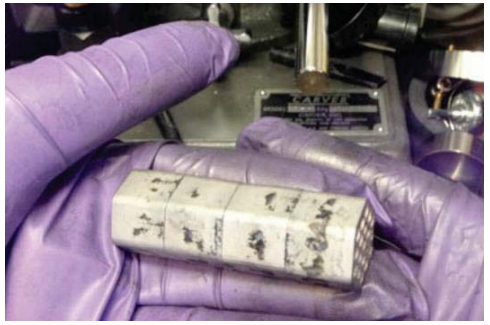


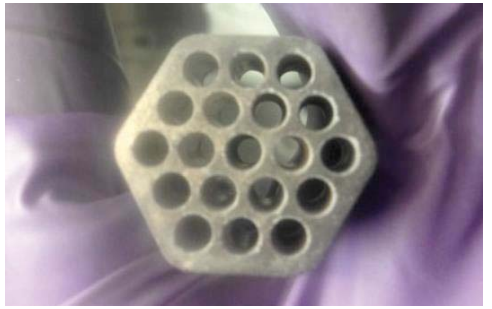


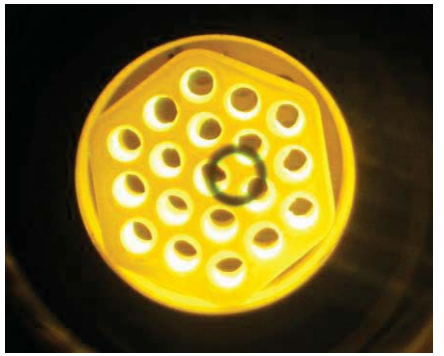
W-UO_2 sample post test

CSNR/Aerojet Rocketdyne W-UO_2 Testing

- W-UO_2 samples fabricated at the Center for Space Nuclear Research in Idaho Falls, ID
 - Spark Plasma Sintering (SPS) techniques
- NERVA heritage 19-hole configuration
- Similar to GE710 fuel fabrication approach
 - Multiple bonded segments
 - Improved sintering with SPS
 - Net shape fabrication (reduced machining)
- 3” sample cycled in CFEET in flowing H_2 to ~2200 C
- Testing terminated due to observed non-uniform heating profile and temperature readings
- Testing of SPS samples will proceed after optimization and verification of CFEET system







Current CFEET Thermodynamic Heating Profile

- Sample location in coil is critical for uniform heating (radial and axial position)
 - 3” long sample located with top edge near top of RF induction coil (6” long)
 - Flowing H2 atmosphere at 16.5 SLPM
- Increased local current (heating) at surface due to melting (gouging effect)

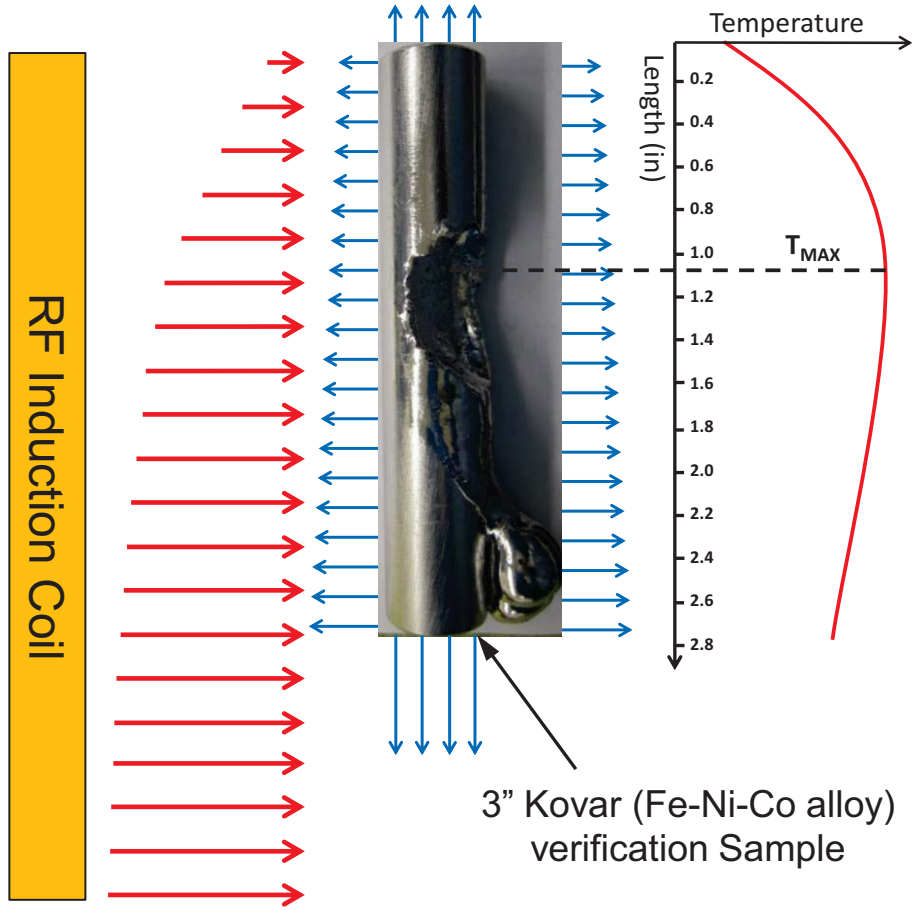
Energy deposition →
Energy loss →

<u>Thermodynamics</u>

Heat Deposition
- Non-linear power density
- Lowest at coil edge
- highest at coil center

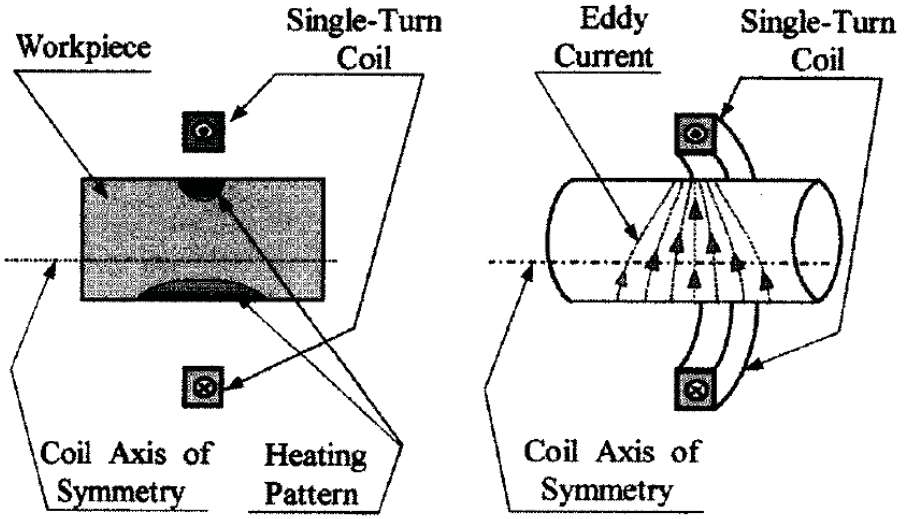
Sides and Top
- Radiation
- Convection

Bottom
- Radiation
- Convection
- Conduction (BN pedestal)

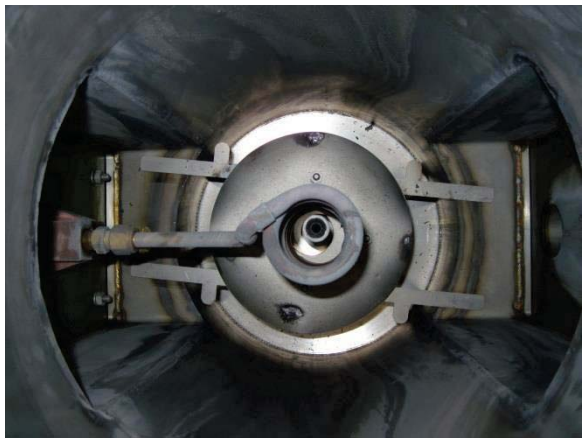


Non-symmetrical RF Heating Effects

- Non-uniform heating due to off-axis alignment of coil and sample
- Eddy currents produce heating of sample through the Joule effect
- Smaller gap between coil and sample results in better coupling
 - Intense, localized heating
- Larger gap between coil and sample results in poor coupling
 - Less intense, more diffuse heating



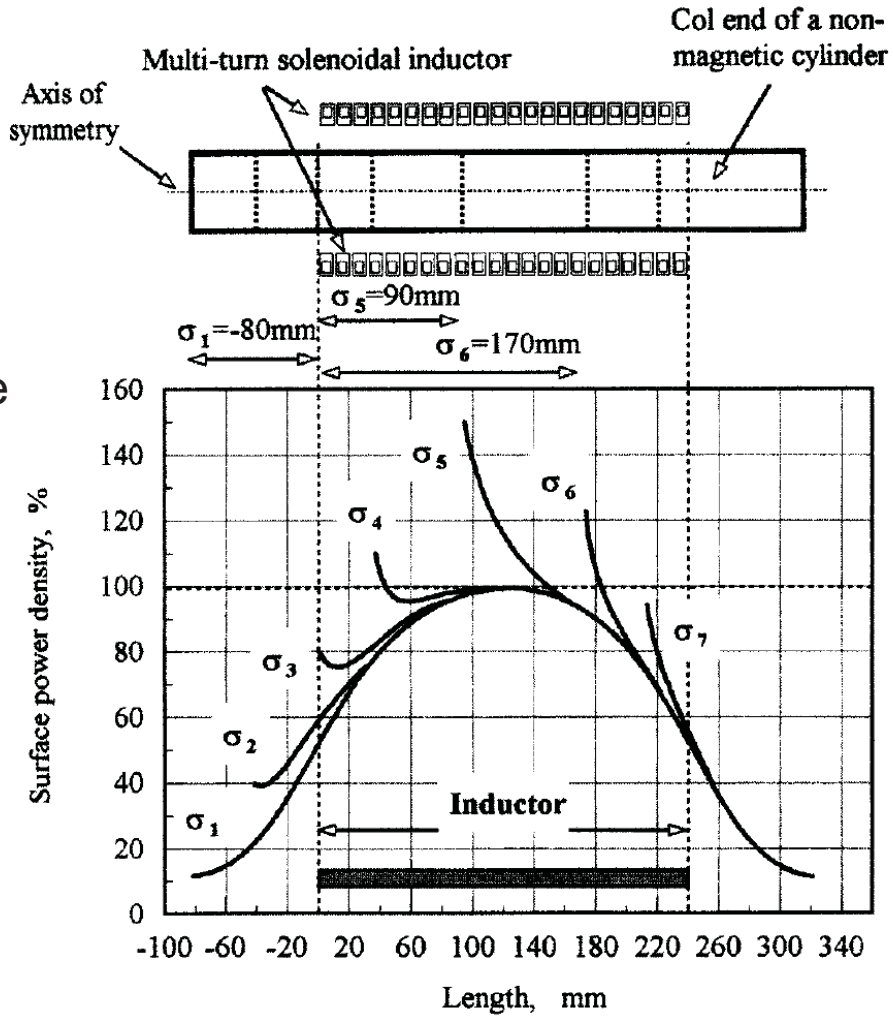
Proximity effect in non-symmetrical single-turn inductor



Rudnev, Valery. "Chapter 3: Theoretical Background." *Handbook of Induction Heating*. New York: Marcel Dekker, 2003. Page 121. Print

Electromagnetic End Effects

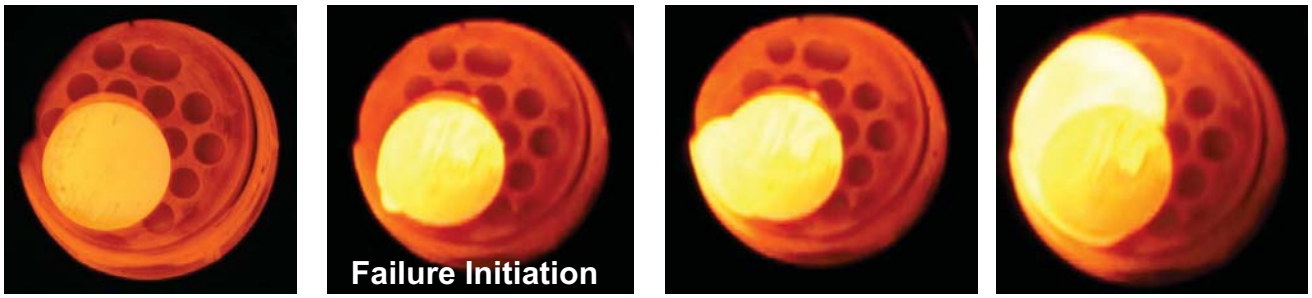
- Coil overhang can affect power density on the sample
- Sample outside of coil
 - Predictable power density curves (σ_1)
- Sample inside of coil
 - Less predictable power densities at the extremes, as seen by $\sigma_3 - \sigma_7$
- Can get under heating or overheating at the extreme ends of the sample
 - Dependent on axial location
- Need to optimize sample location
 - May constrain sample size for current coil configuration (~1.5")



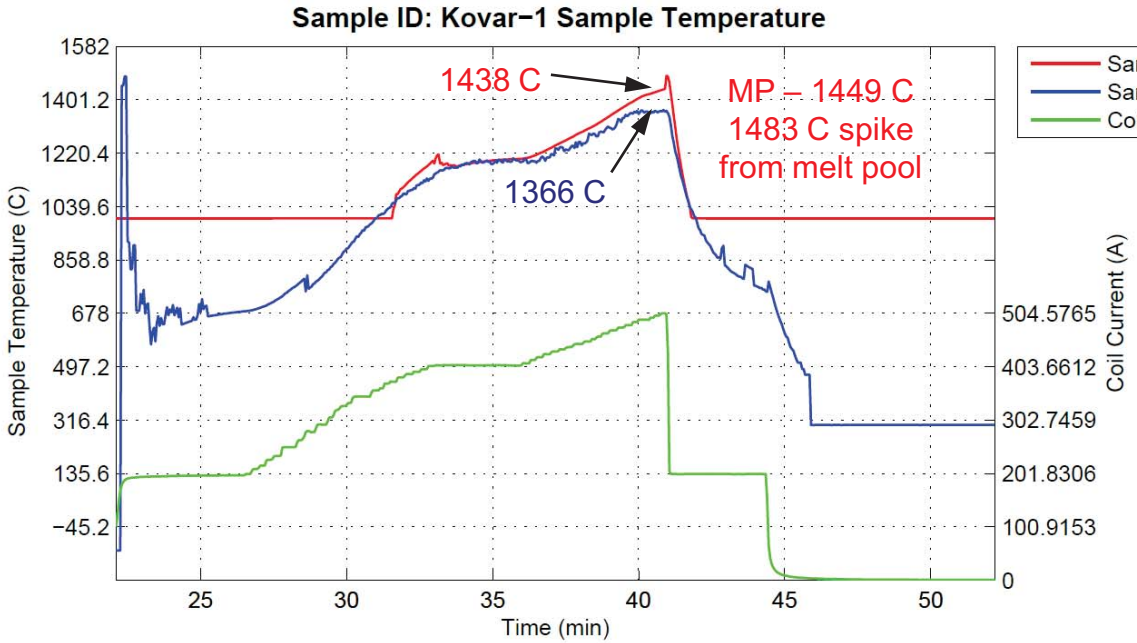
Electromagnetic end effects at different coil overhangs

Rudnev, Valery. "Chapter 3: Theoretical Background." *Handbook of Induction Heating*. New York: Marcel Dekker, 2003. Page 129-131. Print

Non-Uniform Heating Profile Verification



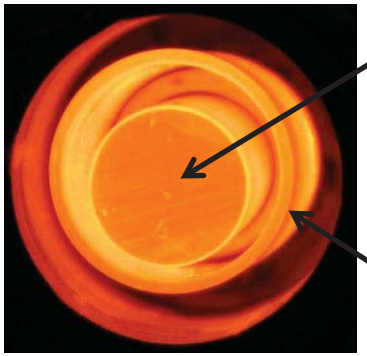
- Kovar sample during induction heating, flowing H2
- 3” sample located with top edge near top of coil





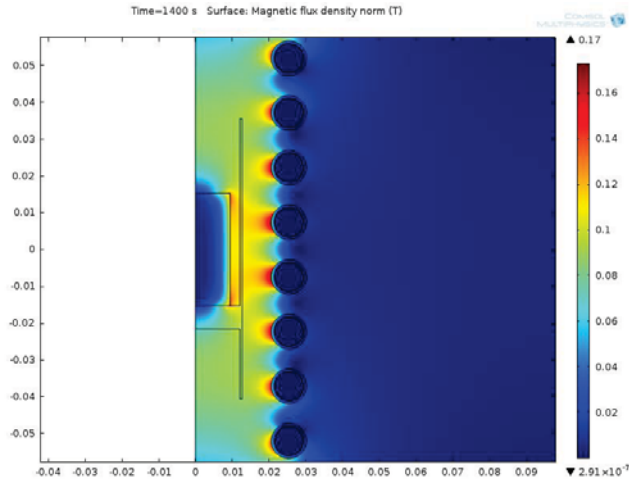
Improve RF Heating Profile with W Susceptor

- Susceptors are used to absorb electromagnetic energy and convert it to radiant heat
- Shield the sample from RF heating
 - Eliminates preferential heating from surface edges, defects, and other anomalies such as joints
 - More uniform heat deposition on sample
- Susceptor evaluation trials in CFEET
 - More uniform heating
 - Eliminated focused current/joule heating failures

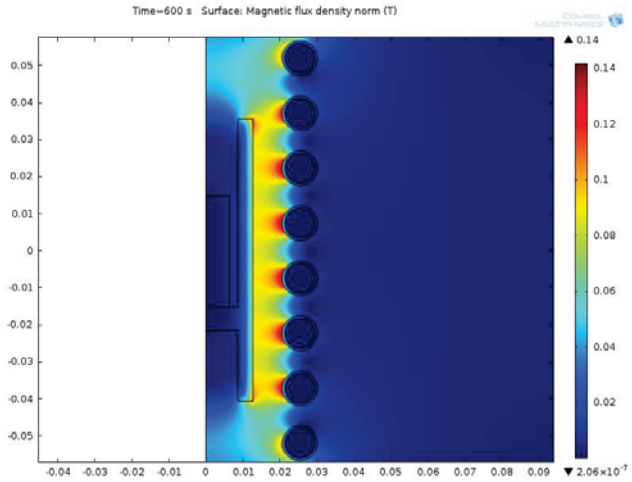








Magnetic flux density on a BN insulator



Magnetic flux density on a W susceptor

Forward Plan and Summary

- Optimize heating profile using a W susceptor and sample size/location
- Upgrade to 3000 C multispectral pyrometers on top and middle
- Complete fabrication and testing of improved subscale W-UO_2 samples
 - W CVD coated UO_2
 - W powder coated UO_2 (binders)
 - With and without integral W claddings
 - SPS and HIP fabricated samples
- CERMETS demonstrated, but not proven to full scale
 - Large variation in materials, processing, and performance
- MSFC has developed subscale hot hydrogen testing capability
 - Rapid, affordable screening
 - Verification of materials and processing prior to expensive nuclear testing
- Development enables fuel optimization for future ground testing and flight technology demonstration